3D ELECTROMAGNETIC DESIGN AND BEAM DYNAMICS SIMULATIONS OF A RADIO-FREQUENCY QUADRUPOLE*

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Abstract

During the design of a low q/m CW 60.625 MHz RFQ for the ATLAS efficiency and intensity upgrade, we have established a new full 3D approach for the electromagnetic and beam dynamics design and simulations of a RFQ. A detailed full 3D model (four meter long) including vane modulation was simulated using CST Microwave Studio, which is made possible by the ever advancing computing capabilities. The approach was validated using experimental measurements on an existing prototype 57.5 MHz RFQ. The effects of the radial matchers, vane modulation and tuners on the resonant frequency and field flatness have been carefully studied. The full 3D field distribution was used for beam dynamics simulations using both CST Particle Studio and the beam dynamics code TRACK. In the final design we have used trapezoidal modulation instead of the standard sinusoidal in the accelerating section of the RFQ to achieve more energy gain for the same length, following the leading work of the Protvino group. In our case, the output energy increased from 260 keV/u to 295 keV/u with minimal change in the rest of the beam dynamics.

ATLAS UPGRADE AND RFQ DESIGN

Details about the ATLAS efficiency and intensity upgrade can be found in [1, 2]. The main design parameters for the ATLAS upgrade CW RFQ for heavy ions are listed in table 1. The RFQ will consist of five identical ~ 76 cm long segments. Figure 1 shows the full five-segment engineering model.

Table 1: Main RFQ Parameters

Parameter / Feature	**Value**
Input Energy (q/m>1/7)	30 keV/u
Output Energy	295 keV/u
Frequency	60.625 MHz
Vane Voltage	70 kV
Power	60 kW
Average Radius	7.2 mm
Length	3.81 m
Transverse normalized acceptance	2 π mm.mrad
Longitudinal RMS emittance	20 π deg.keV/u
Bunching	External

The main design goals are 1) satisfy the beam requirements with the lowest RF power consumption 2) design for a target frequency tuneable to the operational frequency using the designed tuners 3) higher order modes far away from the operational frequency 4) verify the beam dynamics with more than one code and 5) produce accurate vane modulation for manufacturing. Because very few CW RFQ's in the world are working as designed, a very careful design and fabrication procedure is required. A closely interactive and iterative procedure between the electromagnetic design, the beam dynamics simulations, engineering and manufacturing was adopted.

Figure 1: Engineering model of the five-segment RFQ.

THE NEW FULL 3D DESIGN APPROACH

The beam dynamics and the electromagnetic design of an RFQ are usually done separately using different tools. A code such as Parmteq or DesRFQ is used for the beam dynamics design and a code such as Superfish, Mafia or CST Microwave Studio is used for the electromagnetic design. Due to limited computing capabilities in the past, full 3D modelling of a few-meter-long RFQ was not possible. Often a short segment is used for these simulations which need to be verified using a prototype. For the same reasons, vane modulations are often ignored due to the complication and the extreme level of detail they introduce to the geometry.

In the new full 3D approach to be presented in this paper, we have modelled the full five-segment four-meter long ATLAS RFQ in Microwave Studio. The actual vane modulations were also included to study their effects on both the frequency and field distribution. We were also able to produce accurate enough 3D field maps to use for beam dynamics simulations. Integrating the electromagnetic and beam dynamics simulations in the same software provides a more consistent way for design evaluation.

BUILDING THE FULL 3D RFQ MODEL INCLUDING VANE MODULATION

Starting from the single vane model imported from Pro/E into Microwave-Studio, the full four-vane structure is built by simply copying and mirroring the original single vane, figure 2-top. An octagonal RF volume is then defined from which the vanes are extracted to keep only the vacuum volume shown in figure 2-bottom. The

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selected window-coupled structure has the advantages of reducing the transverse size of the RFQ and pushing away higher order modes from the operational one.

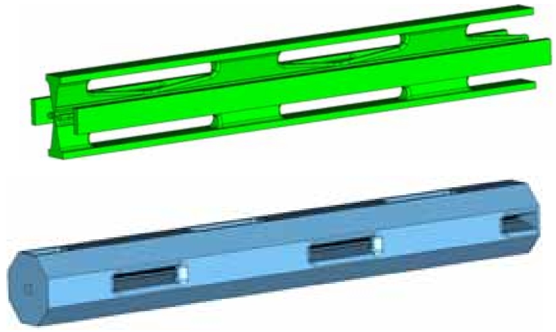

Figure 2: The full 5 segments model built by copying and mirroring the single vane model.

The vane modulation is applied cell by cell. To well describe the modulation curvature, a cell is subdivided into as many sections as needed; the sections are then lofted into a single solid which is extracted from the vane tip at the corresponding location. Figure 3 shows the steps to apply the modulation for a single cell.

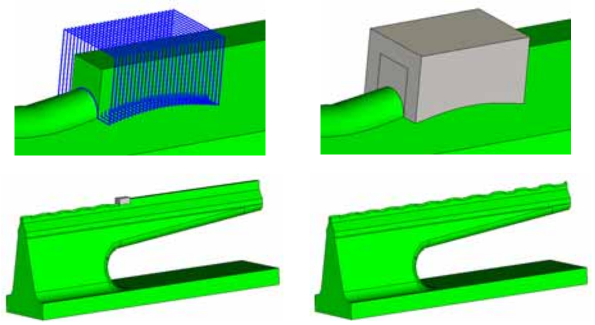

Figure 3: Steps to apply vane modulation for a single cell in the Microwave Studio model.

BENCHMARKING EM SIMULATIONS USING A PROTOTYPE 57.5 MHZ RFQ

Due to the level of detail in the full RFQ geometry even before applying the vane modulation, the choice of the mesh for electromagnetic simulations becomes very important. For this, we have chosen two different mesh types. The first is the automatic meshing (Auto-Mesh) provided by Microwave Studio and the second is to add a finer local mesh in the vane tip area along the whole RFQ (Local-Mesh). The two mesh options produced different results even at our highest number of mesh-cells (32 million) where the difference is about 200 kHz. To understand this discrepancy we needed to benchmark the 3D modelling, meshing and simulation procedure. Fortunately, we can use the 57.5 MHz prototype RFQ built for the RIA project [3] shown in figure 4. Figure 5 shows a comparison of the simulated frequency with the two mesh options at increasing number of mesh-cells to the measured frequency on the prototype RFQ segment. We can clearly see that the Local-Mesh option converges much faster to the measured value than the Auto-Mesh option.

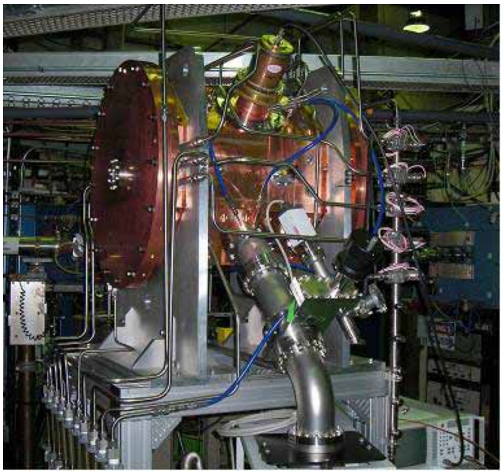

Figure 4: The prototype 57.5 MHz RFQ segment used for benchmarking the 3D modelling approach.

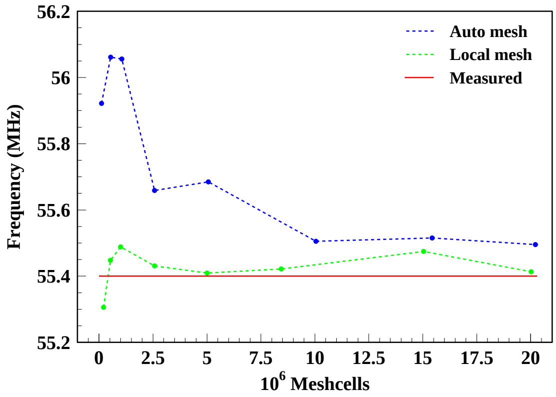

Figure 5: Comparison of the measured prototype frequency with the simulations using two different mesh choices with increasing number of mesh-cells.

EM SIMULATIONS OF THE FULL FIVE-SEGMENTS ATLAS RFQ

Figure 6 shows a comparison of the frequency simulation results for the full ATLAS RFQ using both mesh options at increasing number of mesh-cells. It also shows our target frequency of 60.25 MHz and the tuning range. Despite the fact that we trust more the Local-Mesh result, we have considered the 200 kHz difference with the Auto-Mesh result as a simulation error and we lowered our target frequency by 150 kHz and increased the tuning range from 250 kHz to 400 kHz. From the same simulation, the frequency for the closest higher order mode is about 71 MHz that is more than 10 MHz above the operational frequency.

Table 2 shows the effects of the radial matchers, modulation and tuners on the frequency. The tuners are 5” in diameter inserted 1” deep into the RFQ volume which is half of their 2” full range.

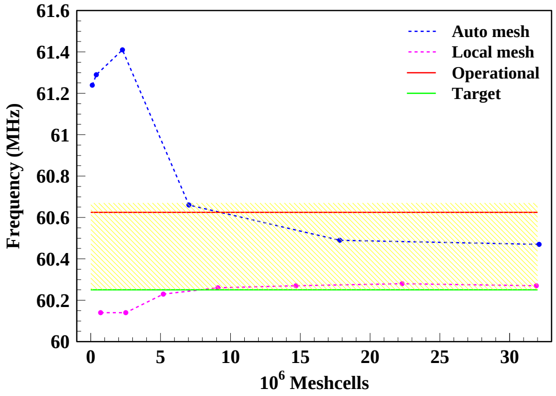

Figure 6: Frequency simulation results for the full ATLAS RFQ model. The band is half the tuning range

Table 2: Different Effects on the RFQ Frequency

Effect	Frequency (MHz)	Frequency shift (kHz)
Plain Vanes	59.77	-
Input Matcher	59.97	200
Output Matcher	60.10	130
Modulation	60.27	170
15 Tuners	60.69	420

To check the field flatness along the RFQ we used the case with both matchers and no modulation which is expected to only introduce fluctuations on the average field amplitude. The simulations shows a 2-3 % tilt in the electric field amplitude along the whole RFQ which is mainly due to the difference in capacitance between the input and output matchers. We found that by using the appropriate set and depth of tuners we are able to tune to the operational frequency and correct the field tilt.

BEAM DYNAMICS SIMULATIONS USING THE FULL 3D RFQ AS A SINGLE CAVITY

As presented in a previous work [1], our final RFQ design will combine sinusoidal vane modulation in the bunching section with trapezoidal modulation in the accelerating section. This approach has already been proposed and successfully implemented by the IHEP-Protvino group [4]. Adopting trapezoidal modulation in the accelerating section increased our RFQ output energy from about 260 keV/u to about 295 keV/u without change in the rest of the beam dynamics. EM simulations showed that the peak surface field will increase by about 15 % from the pure sinusoidal case but will remain below 1.5 Kilpatrick. We should mention that the prototype 57.5 MHz RFQ was tested up to 2.0 Kilpatrick without voltage breakdown. Figure 7 shows the on-axis longitudinal field along the RFQ clearly distinguishing the sinusoidal from the trapezoidal sections.

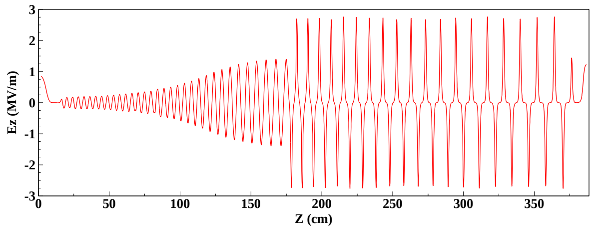

Figure 7: On-axis longitudinal field along the RFQ.

The full 3D field distribution was exported from Microwave Studio into TRACK as a single cavity. The field grid has 4001 points along the RFQ which corresponds to about 20 points for the shortest cell. Despite the lower accuracy of the single cavity 3D fields we were able to get very similar beam dynamics results as the simulation using the cell by cell 3D field from EM-Studio. Table 3 shows a comparison between the single cavity and cell by cell 3D simulations. The lower transmission and the larger longitudinal emittance for the single cavity case may be due to the lower precision of the 3D fields extracted for the full model.

Table 3: Comparison of the Cell by Cell and the Single Cavity Beam Dynamics Simulations Results

Quantity/ Feature	EM-Studio Cell By Cell	Microwave Studio Single Cavity
W-out (keV/u)	296.5	296.5
Transmission (%)	83	79
Longitudinal ε-rms (π deg.keV/u)	18.6	22.4
Transverse ε-rms (π mm.mrad)	0.21	0.22
Output Beam	Symmetric	Almost Sym.

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